Whispering Gallery Mode Resonators for Frequency Metrology Applications

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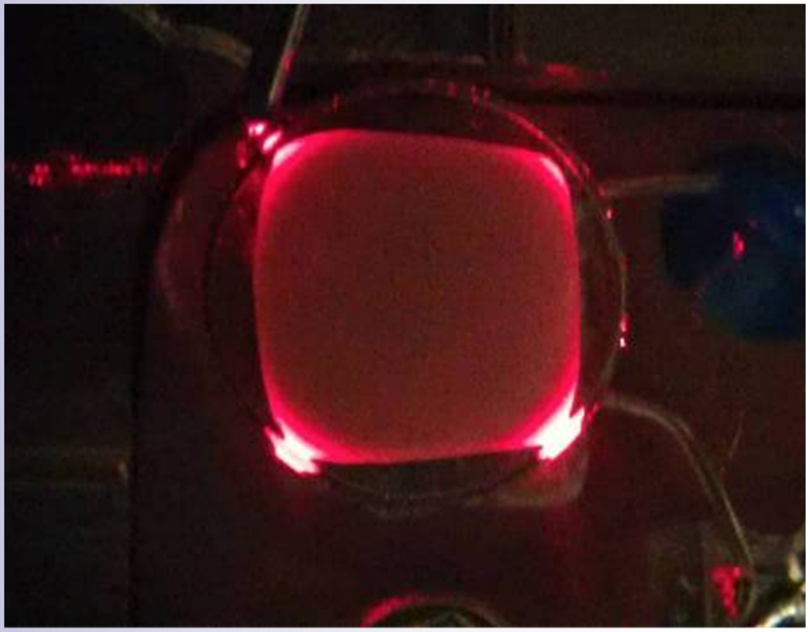
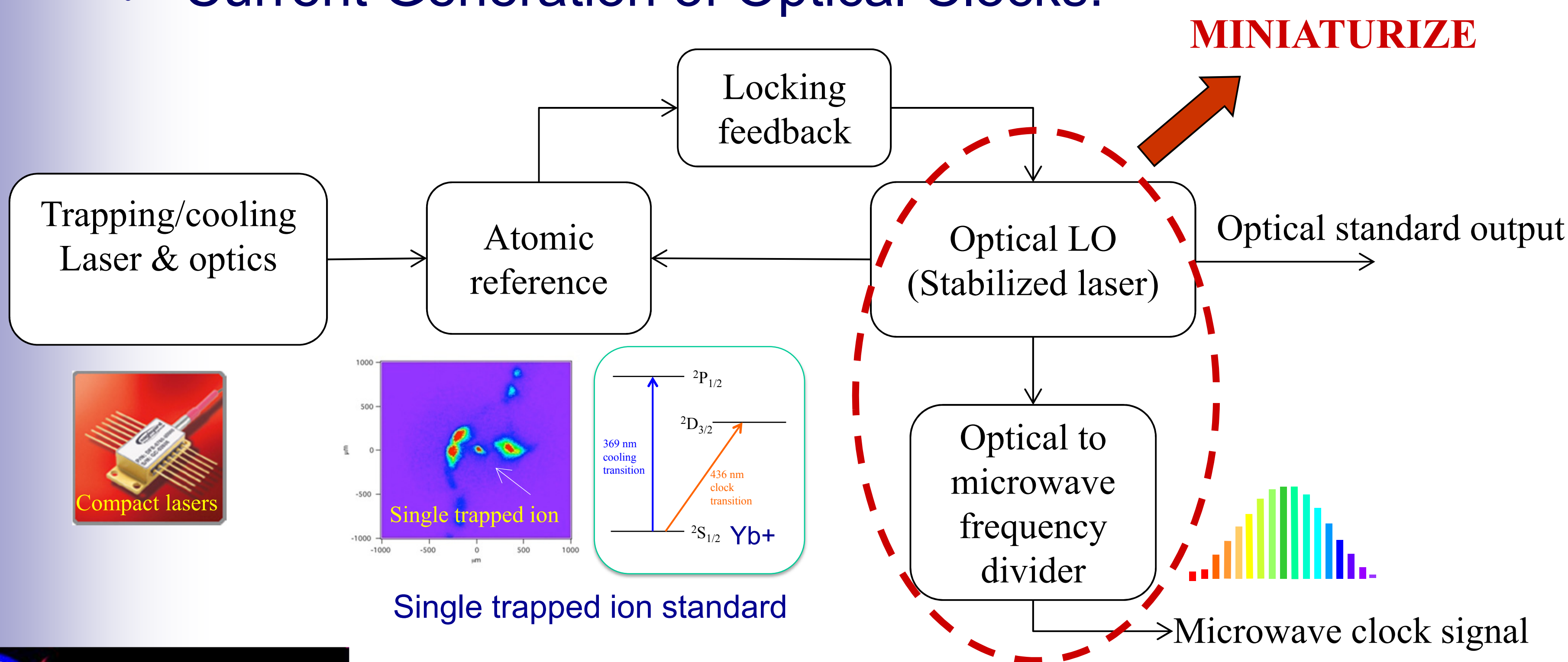


KISS Quantum, 2012

Jet Propulsion Laboratory
California Institute of Technology

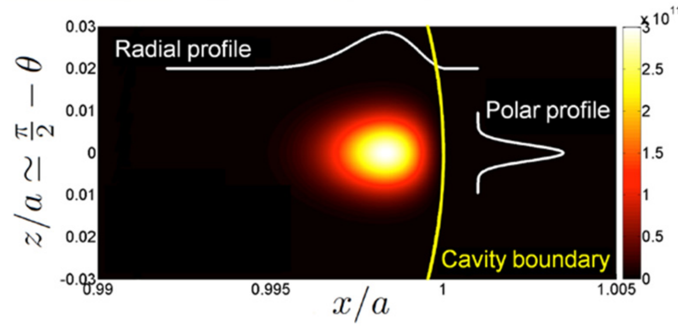
Motivation

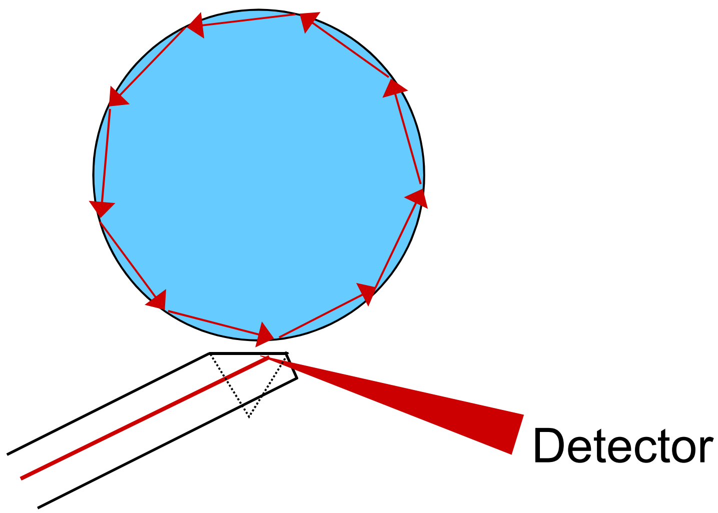
- Better Clocks for deployment into space
  - Size: < 10 kg
  - Power: < 20 W
  - Performance: $\Delta f/f < 10^{-16}$
- Current Generation of Optical Clocks:



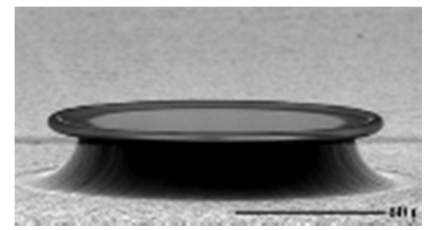
Whispering Gallery Mode Resonators

- Dielectric Sphere, Disc, Torroid, Waveguide (10's μm to cm scales)
- Light confined by total internal reflection
- High Q, lifetimes several μseconds

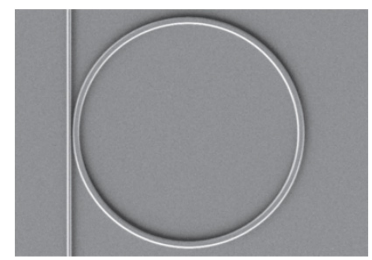




- Evanescent Coupling into Resonator:
  - Tapered Fiber Waveguide
  - Prism (angle-polished fibers)



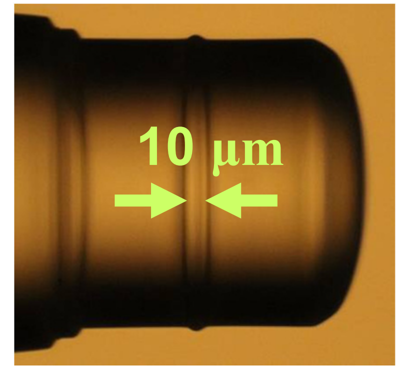
Vahala, CalTech



Gaeta, Lipson, Cornell

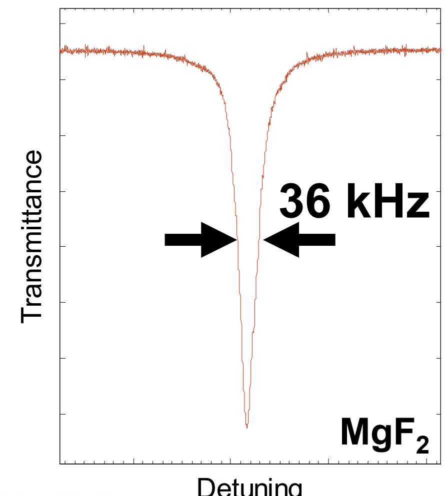
JPL

WGMRs Applied



Unique and Useful Properties:

- Tight mode localization, high power/volume
  - Nonlinear effects:
- Parametric oscillation
  - □ combs
  - □ harmonic generation, etc.
- Ultra-high quality factor, finesse
- Frequency reference, sensing
- Material Flexibility:
  - Active materials, lasing WGMRs.
  - Crystalline Materials
    - □ Birefringent resonators



WGMR Microcombs

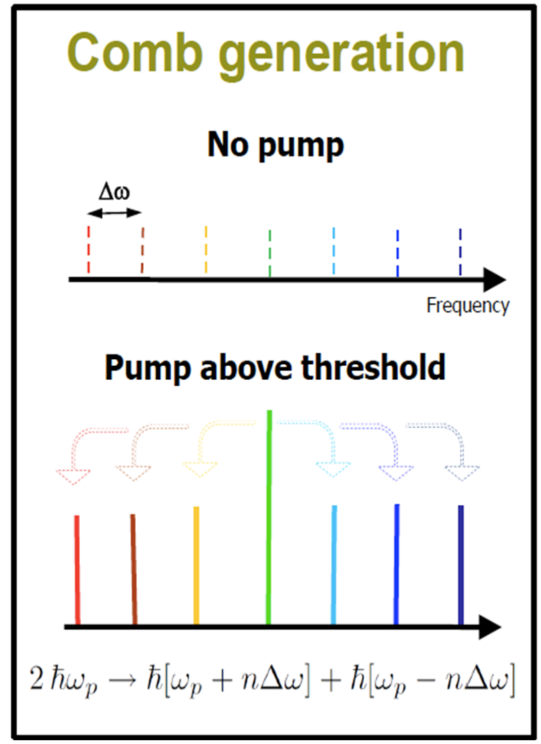
Comb formation from cavity enhanced four-wave mixing, Kerr non-linearity

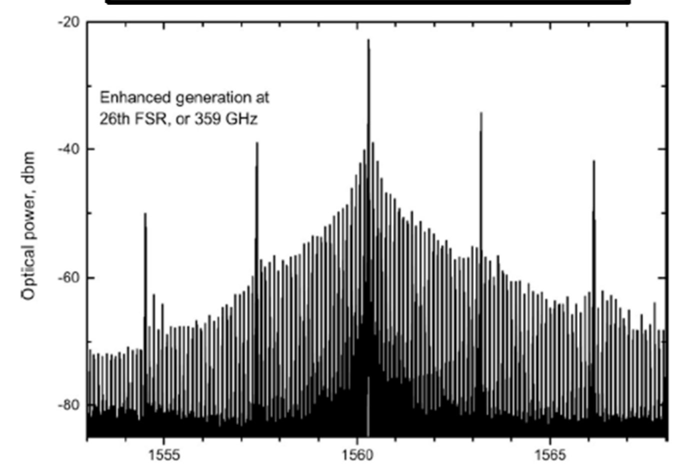
<u>Advantages:</u>

- CW pump laser
- Compact Size
- Monolithic, Robust

<u>Challenges:</u>

- Dynamics not well-understood
  - Coherence
- Path to stabilized comb unclear
  - Octave spanning?
  - Other stabilization method?





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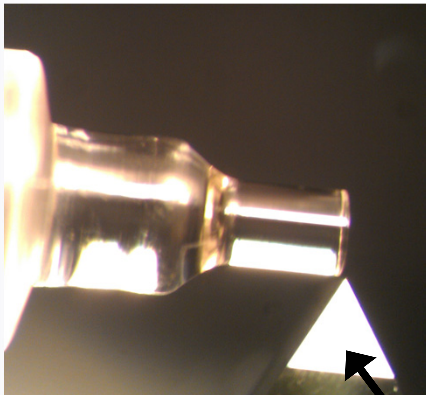
Recent Microcomb Result

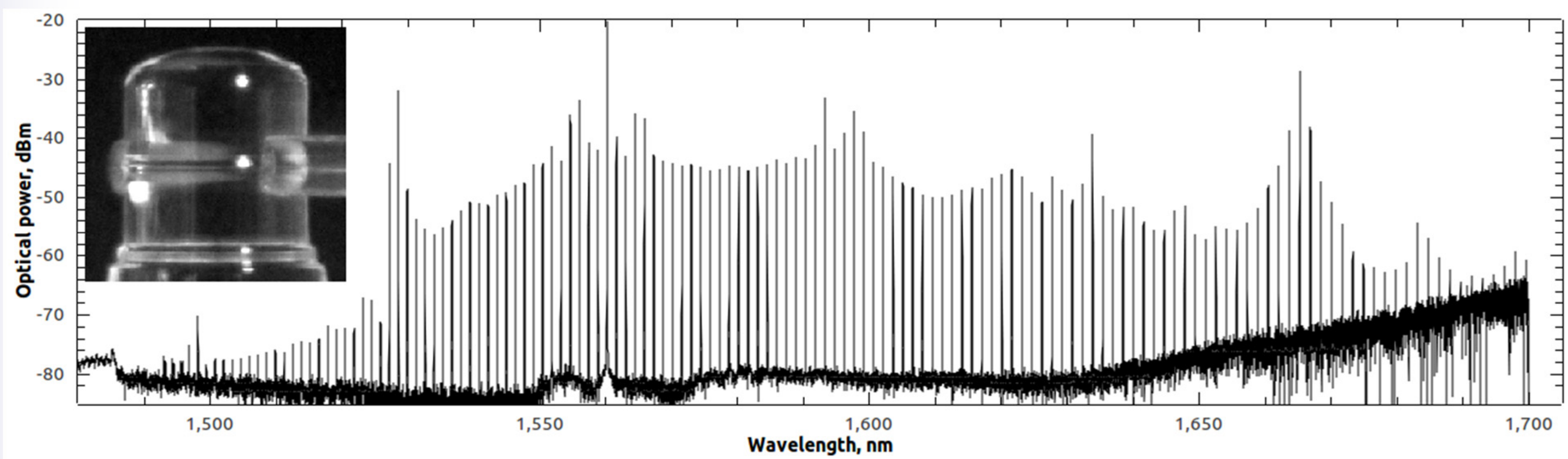
- 200 nm width from 52 mW pump
- Single mode resonator
- N=1 comb, first tooth appears at 1 FSR.
  - ➔ Coherent comb expected
- FSR = 172 GHz

Large tooth-spacing good for astronomical spectrometer calibration



Diamond Cutter

Microcomb



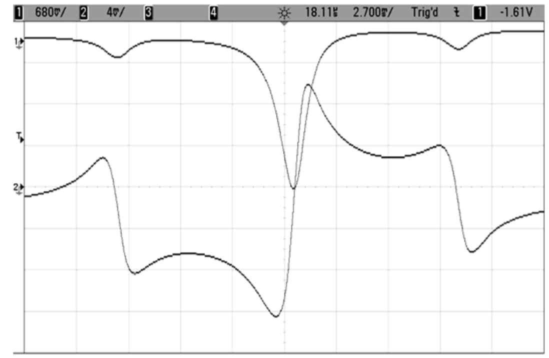
[Grudinin et al., *Opt. Exp.,* Vol. 20, pp 6604 (2012)]

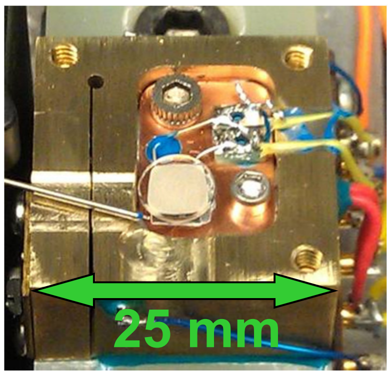
WGMR Frequency Reference Cavities

Benefits:

- High Q facilitates tight locking
- Wide transparency range
  - Single cavity for many λ's.
- Solid Structure is Robust
  - Vibrationally insensitive
  - Acoustically insensitive

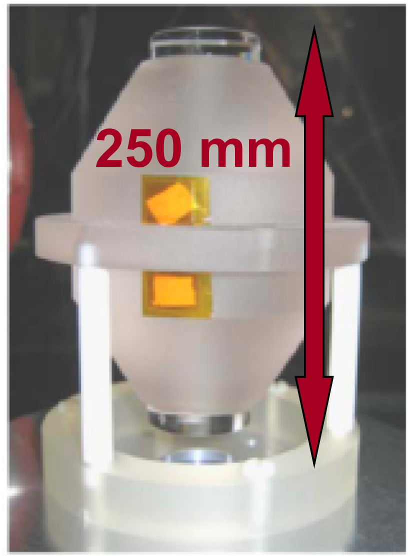
Ultra Compact





WGMR Cavity

vs.



FP Cavity

Challenges:

- Light travels in solid media
  - Thermal sources of instability
  - Material imperfections/drifts

Thermal Considerations

$$\frac{1}{f}\frac{df}{dT} + \underbrace{\frac{1}{R}\frac{dR}{dT}}_{\alpha_l} + \underbrace{\frac{1}{n}\frac{dn}{dT}}_{\alpha_n} = 0$$

Thermal-expansion (α_l)

Thermo-refraction (α_n)

f = *resonance freq.*

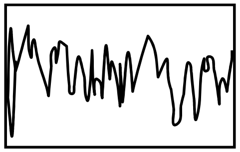
R = *disc radius*

n = *refractive index*

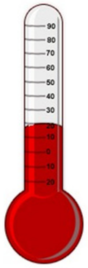
Fundamental:

$$\left\langle (\Delta T)^2 \right\rangle = \frac{k_b T^2}{C_p V \rho}$$

Technical:



Laser Intensity Noise



Macroscopic Disc temperature

Temperature Fluctuations

Frequency Fluctuations, Noise

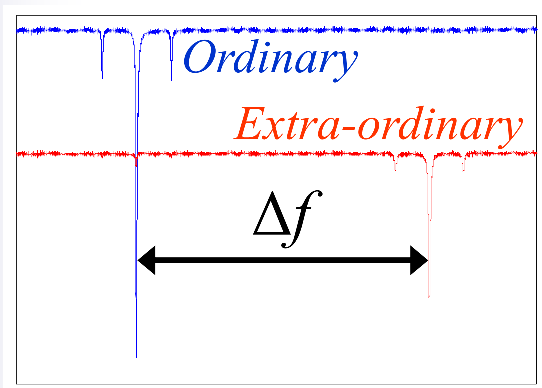
Precise temperature control is paramount!

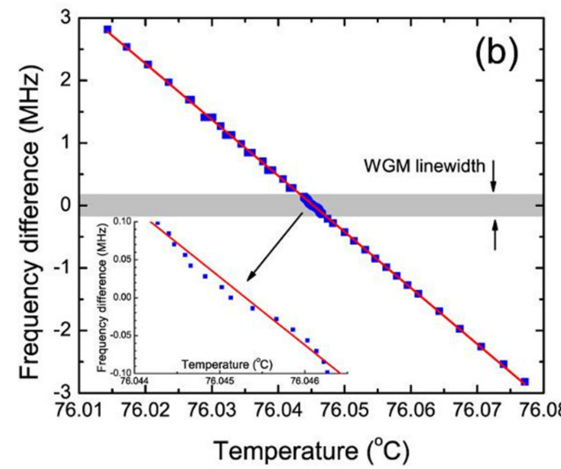
Dual-mode stabilization

Thermo-refraction → Differential TempCo

$$\frac{d}{dT}\Delta f = \pm\frac{c}{\lambda}\left[\alpha_n^{(o)} - \alpha_n^{(e)}\right] \approx \begin{cases} 79.8\ \text{MHz/K (literature values)} \\ 89.8\ \text{MHz/K (measured value)} \end{cases}$$

MgF_2





Sampling Mode-Volume Temp

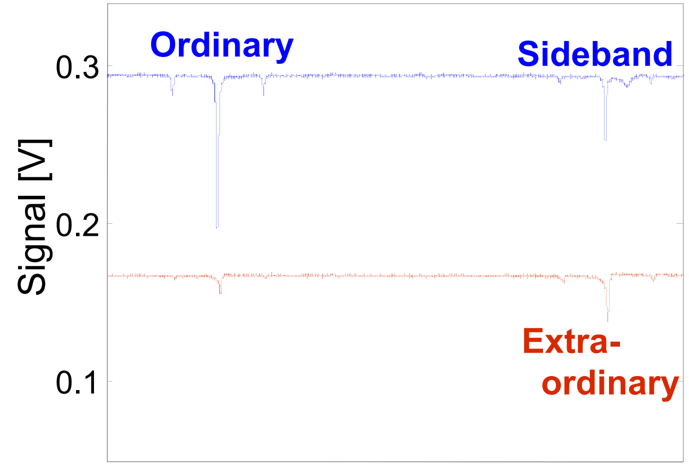
Birefringent crystal

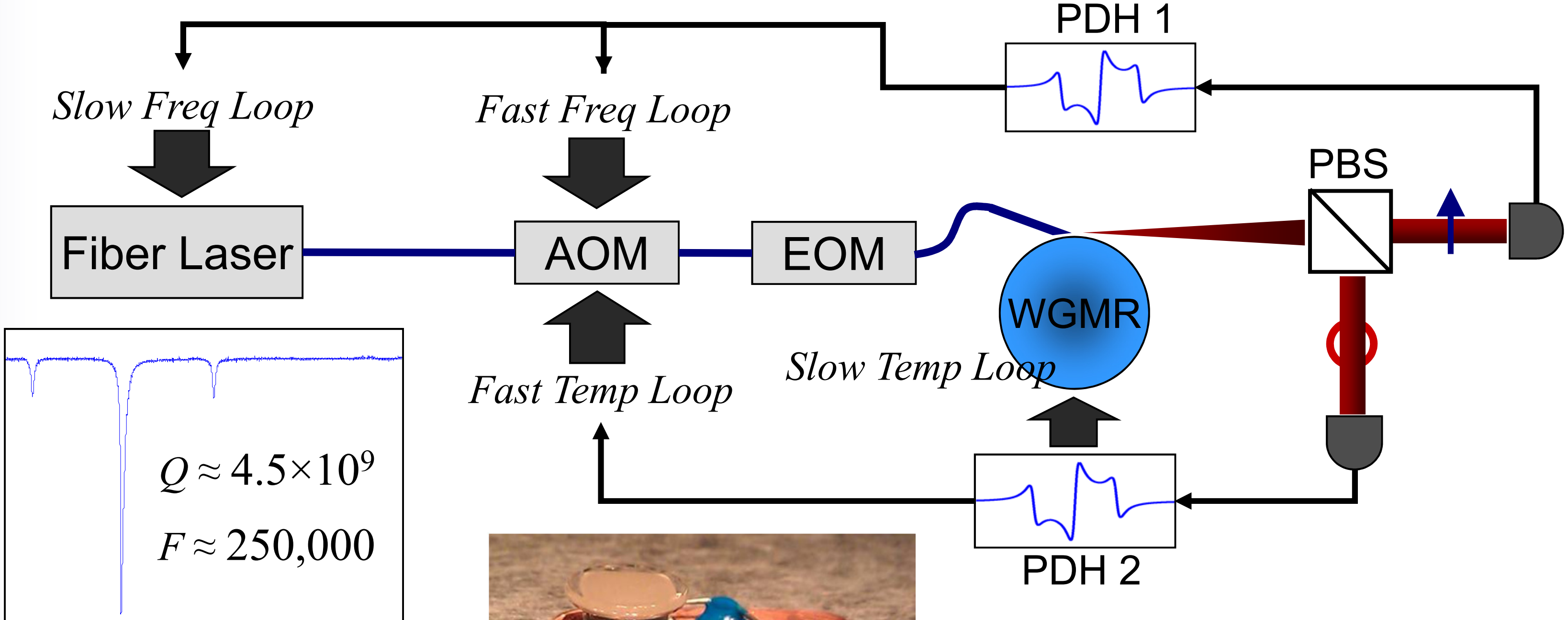
Resonator Temperature → Measure Δf → Feedback → Resonator Temperature

[Strekalov et al., *Opt. Exp.*, Vol. 19, pp 14495, 2011]

Stabilization Scheme

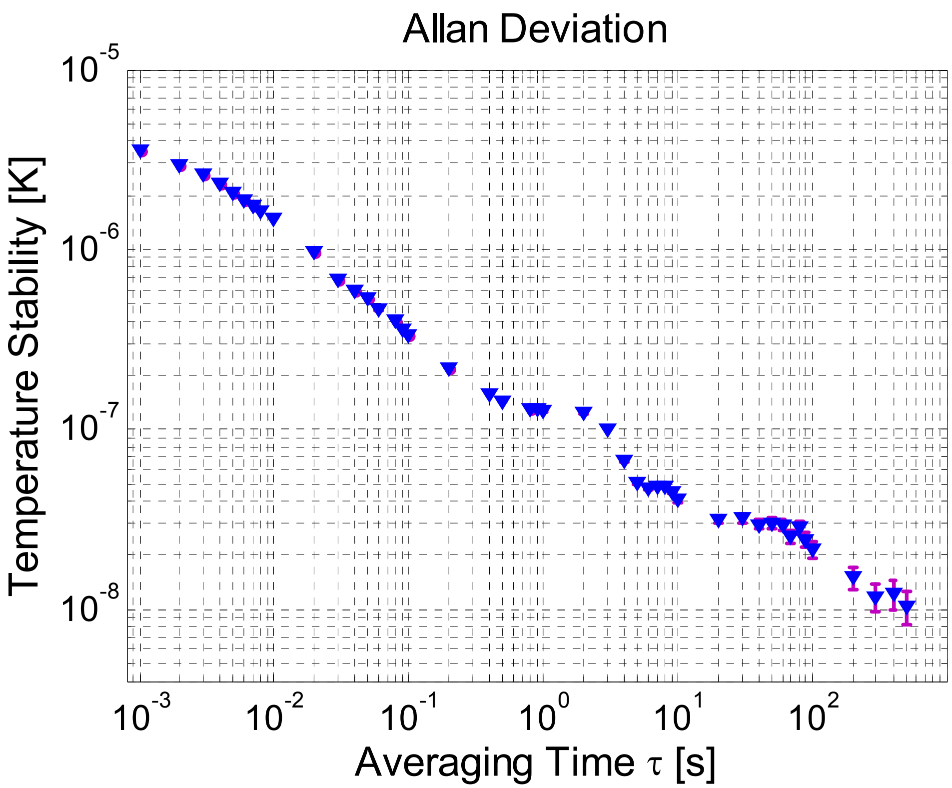
- Single Modulated Laser
- "Carrier" is locked to ordinary mode
- Sideband excites extraordinary mode
  - Second error signal for temp lock
- Both loops have fast/slow branches





Temperature Stabilization Result

- Based on error signal residuals
- Locked laser scheme averages down to nK range
- Increased thermal BW from TEC means 2 decades faster averaging than heater alone



10 nK stability at 300 s

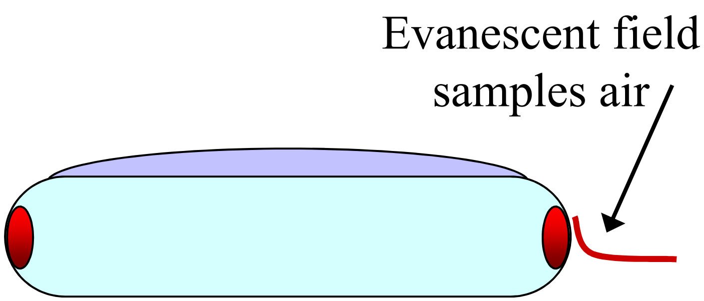
~8.7×10^{-14} optical frequency stability

Optical Frequency is not correspondingly stable

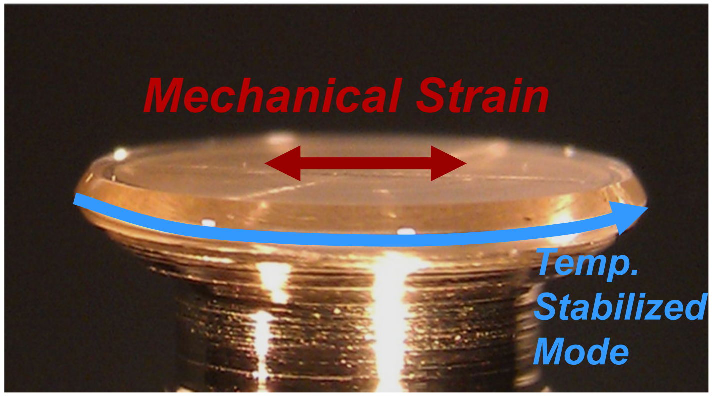
Optical Stability Error Sources

Common-mode Drifts are not Corrected

- Refrective index changes in the:
  - Host material
    - Non-linearities, photo-refraction
    - Interaction with other fields (magnetic, acoustic, e.g.)
  - Surrounding Gas



- Mechanical deformations from:
  - Temperature Gradients in disc
  - Strain in mounting structure
  - Aging



$$10^{-14} = \frac{\Delta f}{f} = \frac{\Delta R}{R}$$ ⇨ Radial stability ~10^{-16} m needed!

Conclusions, Future Work

- WGMR microcomb
  - › Achieved desired spectrum from cavity dispersion engineering
  - › Characterize coherence, investigate stabilization methods
- Dual-Mode Temperature stabilization:
  - › Achieved High temperature stability of *Mode Volume*
  - › Investigate optical frequency pulling sources